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NAVAL AIR SYSTEMS COMMAND
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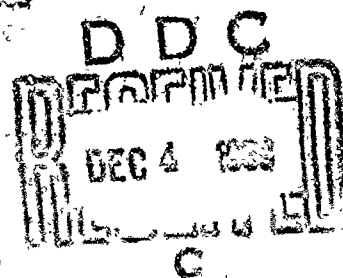


PROFESSIONAL DEVELOPMENT CENTER

SPECIAL PROJECT NO. 69-04

**A SURVEY OF REVERSE FLOW PROBLEMS
WITH HIGH SPEED ROTARY WING AIRCRAFT**

This document is prepared to provide information and data
to the Naval Air Systems Command, Department of the Navy,
Washington, D.C. 20360.



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HIGH SPEED ROTARY WING AIRCRAFT

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NavAir

Navy Department

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FOREWORD

The Professional Development Center is the primary source of young civilian engineers and scientists for the Naval Air Systems Command. At one point in their training program, they undertake an original Special Project as part of the requirements for an accelerated promotion. Some of the reports on these special projects have been both interesting and informative, and deserve somewhat wider distribution. The results presented herein are not intended to reflect official US Navy policy, nor necessarily even the views of the Naval Air Systems Command. The results of the Special Project are presented herein because they are interesting, and because they may constitute a small contribution to the literature.

ABSTRACT

A survey of the problems and concepts (design solutions) related to the reverse flow region on high speed rotary wing aircraft has been made. For each design solution, the performance benefits and engineering problems are discussed. Since the technical approach is non-analytical and uses results from many sources, the recommendations are made as a best-judgement on the basis of the data presented herein. A chart of ten problem areas common to all the design solutions which has been developed indicates the following. Resources should be allocated to the design and testing of a high stiffness rotor blade capable of operating at low rotational speeds and advance ratios greater than one, and an investigation of the cyclic-collective blade pitch control interchange which begins as the advance ratio approaches one. The information obtained and the experience gained will be applicable to the largest number of design solutions. The offset-shaft rotor (operating at $u < 1$) has the least number of problems and may be the most feasible design solution. ()

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INTRODUCTION

Combining a vertical take-off and landing capability with the high speeds and efficient cruise of a conventional aircraft has been a recurrent goal of planners and designers. Many plausible VTOL aircraft concepts have been proposed, designed, and built; but the helicopter is the only VTOL aircraft in operational use today. There are several reasons why the helicopter remains the only operational solution having satisfactory flight characteristics in both vertical and cruise flight modes while still maintaining a useful payload-lifting capability. One basic reason is the superior lifting efficiency (vertical thrust/power required) of the low disc loading rotor when compared to other thrust generators with higher disc loadings. (See Figure 1) Except for missions with very nominal VTOL requirements, the low disc loading designs will dominate the VTOL field. Even for nominal hovering requirements, the use of high disc loading VTOLs is questionable because of their high downwash velocities. High downwash velocities constitute a problem to ground personnel, may require special airfields, create a loss in pilot visibility from the dust clouds generated, and may result in damage to the propulsion system caused by flying debris. Finally, low disc loading VTOLs have excellent low speed control capabilities and superior emergency power-off landing capabilities.

Currently, the cruise characteristics of the rotor severely limit its total performance. This is exemplified by the speed envelope of pure helicopters. If a low disc loading VTOL aircraft can be designed with a high speed cruise capability while having a moderate weight and complexity penalty, it should provide a better transportation effectiveness and a greater mission versatility than present low speed helicopters or high disc loading VTOLs. The problem, then, is to break out of the restricted speed envelope of the low disc loading rotor.

The purpose of this report is to provide a survey of the problems and concepts related to the reverse flow region on high speed rotary wing aircraft with the intention of identifying a most-plausible avenue for future development. Since the technical approach is non-analytical and draws on results from many sources, the recommendations are made as a best-judgment on the basis of the data presented herein.

PROBLEM STATEMENT

Assuming that adequate power is available, the forward speed of a rotary wing aircraft reaches a limit when the drag rise, vibration levels and loss of lift become unacceptable. The forward speed increase is limited by two phenomena -- both generic characteristics of horizontal rotors.

- 1) The retreating blade stalls at high forward speeds.
- 2) The advancing blade reaches its critical mach number.

With increasing forward speed, the retreating blades of a rotor encounter lower and lower net airflow velocities which increase the blades' tendency

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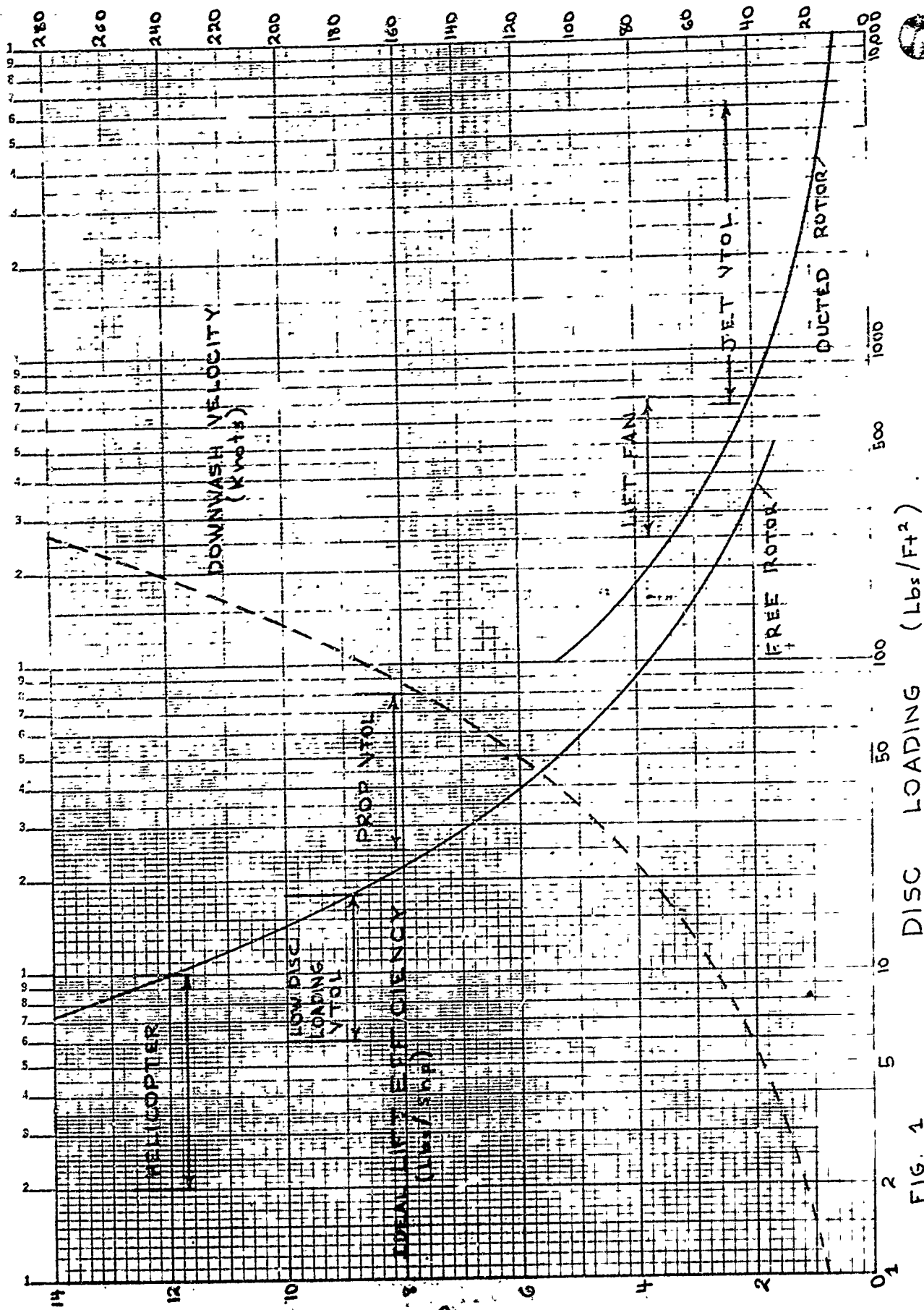


FIG. 1

to stall. In order to maintain symmetry of lift (zero rolling moment), it is necessary to increase the retreating blade angle of attack. As forward speed is increased, the angular changes also increase. At some point the blade angle of attack reaches a maximum value. Above that value the retreating blades exhibit an unacceptable amount of stalling. For a given forward speed, increasing the blade's rotational speed will alleviate this problem. However, the rotational speed is limited by the total velocity on the advancing blades which increases as forward speed increases. As the total velocity approaches the speed of sound, the advancing blades are subjected to buffeting and an excessive drag rise.

Consequently, we have an aerodynamic "vicious circle" where the solution to one problem aggravates the other problem. Figures 2 and 3 illustrate the lift problems arising from the unsymmetrical aerodynamic flow. In Figure 2 reverse flow (the net airflow is from the blades' trailing edge to the leading edge) region boundaries are plotted as a function of advance ratio--the ratio of the aircraft's forward speed to the blades' tip rotational speed. For normally twisted blades and typical cyclic pitch variations, any lift which the retreating blades produce must be done outside the reverse flow region. Figure 3 is a plot of the ratio of the blade dynamic pressure to the free stream dynamic pressure for the advancing blade at 90° and the retreating blade at 270° . Because of the mach number limit and retreating blade stall, developing sufficient lift while maintaining level (no roll) flight is a fundamental problem for lifting rotor aircraft.

SOLUTIONS CLASSIFICATION

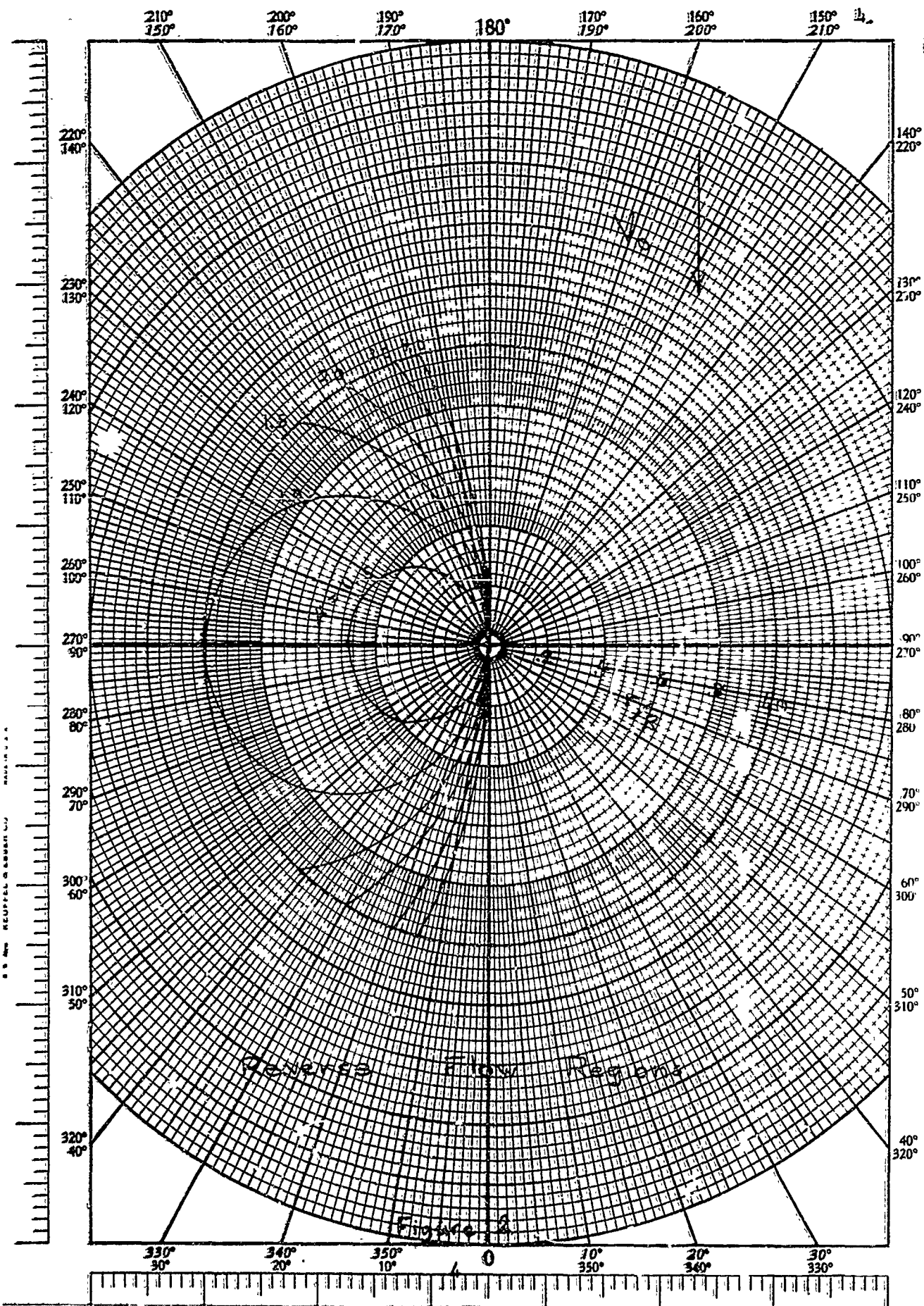
Many solutions have been proposed for this problem. The design solutions may be divided into three functional classes. A description of each functional class and the solutions which will be discussed follows:

Class I: Class I solutions are those design solutions which extend the flight speed envelope of the lifting rotor by modifying its propulsive or lifting requirements or both. Included in this class is the family of compound helicopters--unloaded, unloaded and slowed, etc.

Class II: Class II solutions are those design solutions which extend the speed envelope by modifying the rotor to delay the lift imbalance or mach number limitation. The following concepts are discussed

1. Advancing Blade Concept
2. Controllable Twist Rotor
3. Jet Flap Rotor
4. Forced Lead-Lag Blade
5. Offset-Shaft Rotor

Class III: Class III solutions are those design solutions which eliminate



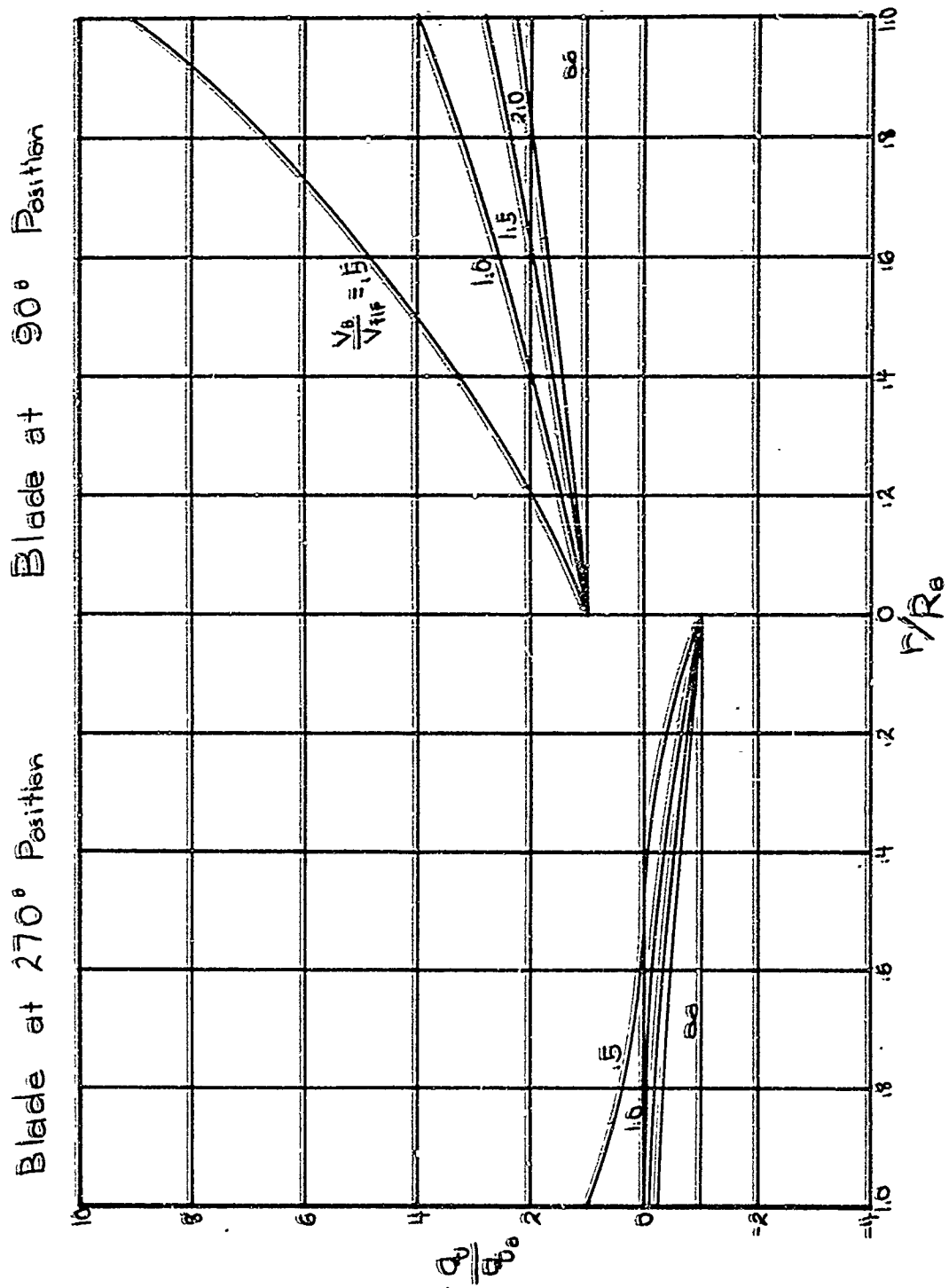


Figure 3: Ratio of Blade Dynamic Pressure to Free Stream Dynamic Pressure

the whirling rotor in forward flight by some geometrical transformation.
Included in this class of design solutions are:

1. Rotor/Wing (Lockheed)
2. Rotor/Wing (Hughes)
3. Tilt Prop-rotor
4. Trailing Rotor
5. Stowed Rotor

CLASS I DESIGN SOLUTIONS

Class I design solutions are composed primarily of those vehicles known as winged helicopters or compound helicopters. These vehicles (see Chart I) extend the helicopter speed envelope by removing either the rotor lift requirement, the rotor thrust requirement or both. Using these techniques the speed envelope may be extended up to 100% above its present boundary. This extension does not represent a forward speed breakthrough, but the considerable speed increases are achieved without major development problems. The engineering problems are relatively straightforward when compared to Class II and Class III solutions. In each case the auxiliary wing or thrusting device decreases the work requirements of the rotor.

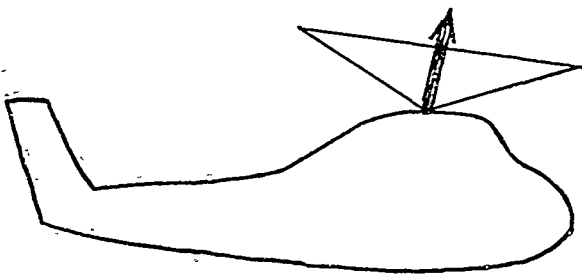
By examining the speed envelope extension of the Lockheed XH-51A series of helicopters, the mechanisms yielding a speed improvement for Class I design solutions may be determined. Figure 4 is a grid of helicopter forward speed versus the advancing blade tip mach number, and lines of constant advance ratio are plotted. Spotted on this grid are the members of the XH-51 family of helicopters.

Indicative of the maximum speed of a pure helicopter, the XH-51A reaches a forward speed of 201 mph. With a blade tip speed of 650 ft/sec, the XH-51A's performance is plotted slightly under the intersection of the lines $M=0.85$ and $u=0.50$. This region seems to represent the practical limit of pure helicopter performance. Blade stall may be minimized by careful design, but the generation of sufficient lift and thrust is difficult. Increased forward speeds require greater thrust levels, and an equivalent lift from a smaller portion of the blade.

The addition of an auxiliary wing allows the rotor blades to be unloaded. As the lift required by the rotor decreases, the required blade angles of attack decrease (assuming a constant rotor tip speed). Consequently, the blade tip mach number for a given acceptable compressibility drag rise increases. Some forward speed increase may be achieved by the addition of a wing alone, but an auxiliary thrusting device is necessary to compensate for the increased drag at higher flight speeds. With the addition of a wing and an auxiliary jet engine, the XH-51A increased its maximum forward speed to 272 mph. To achieve this speed, the blade tip mach number increased to .93 and the advance ratio increased to .61. Although more of the retreating blades were in reverse flow, this was more than compensated for by the unloading of the rotor.

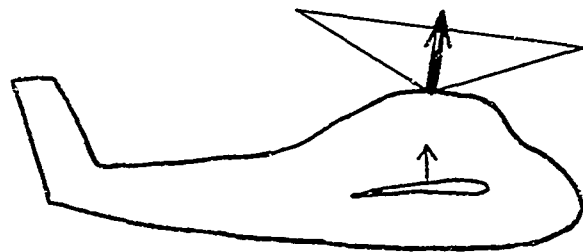
A mach number of .93 does not represent a significant limit on the rotor blade tip speed. A Bell helicopter using a specially designed high speed blade with a 6% tip thickness to chord ratio obtained a tip mach number equal to .98 during forward flight. The blade exhibited satisfactory compressibility characteristics, and steady flight at this speed was felt to be feasible. Using a high speed blade with a thin tip to achieve a tip

CHART I



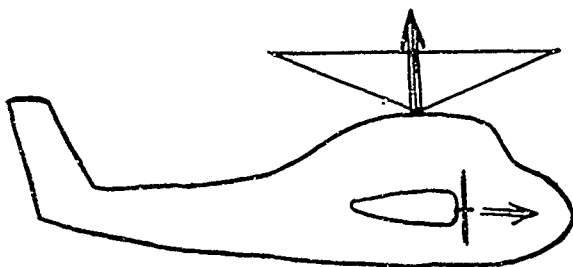
Helicopter

175-200 mph



Helicopter and Wing

175 - 200 mph



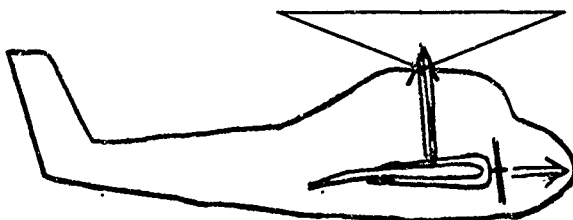
Helicopter & Propulsion

190-225 mph



Semi-compound

200-300 mph



Compound Helicopter

250-400 mph

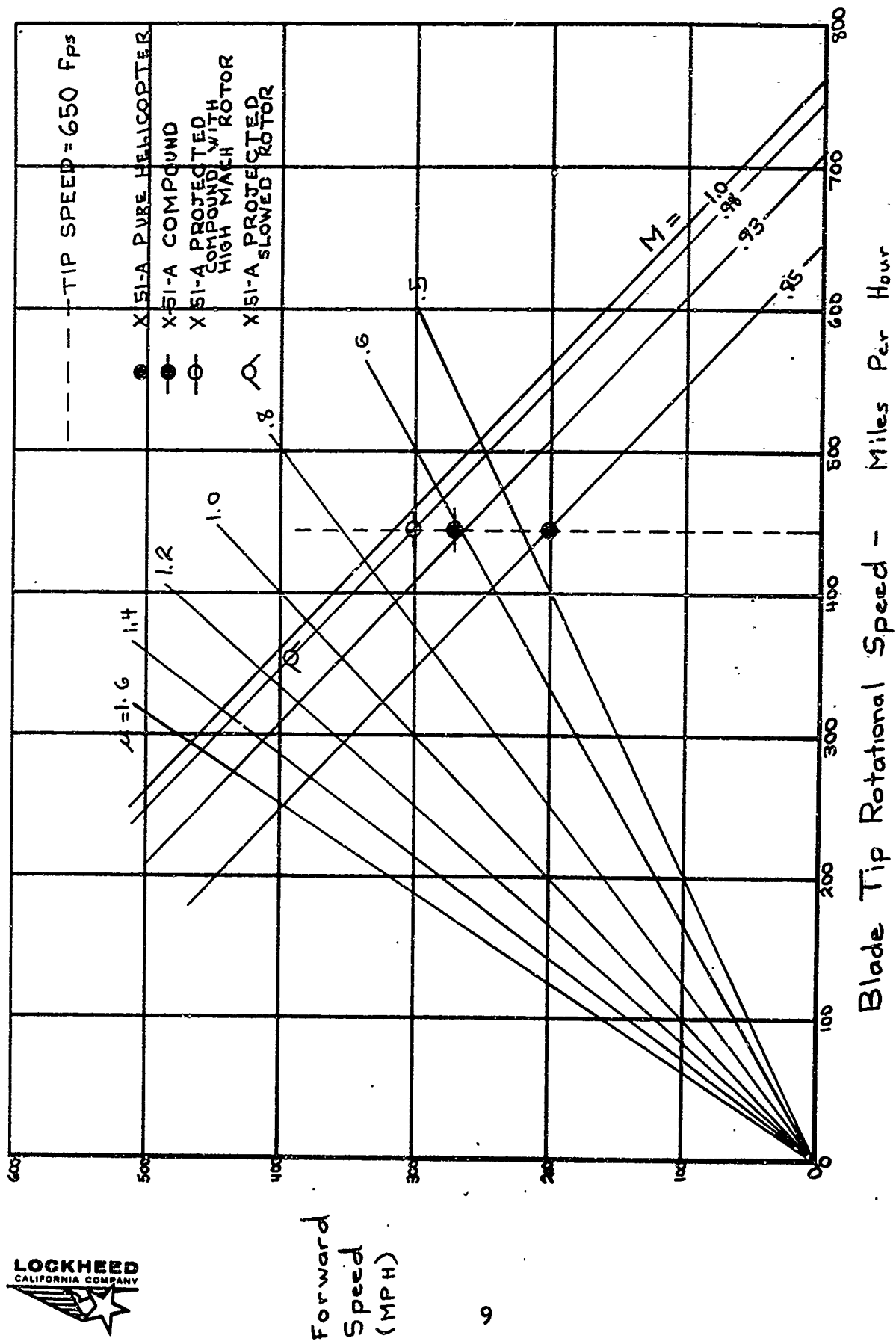


FIGURE 4

mach number equal to 0.98, the XH-51A should be able to fly at a forward speed equal to 304 mph.

Although supersonic blade tip speeds have been used on some research vehicles, blade tip mach numbers greater than .98 are not likely to be used on practical vehicles because of the large wave drag penalties. Consequently, further forward speed increases may only be obtained by reducing the blade tip rotational speed. Normally, the blade rotational speed is determined both by hovering and cruising requirements. A low tip speed is favorable in forward flight but penalizes the hovering performance. 600 ft/sec is near the minimum practical tip speed for conventional, geared rotors.

The solution to the problem is the "slowed rotor" concept. The XH-51A compound with a tip mach number equal to .98 may increase its forward flight speed to 400 mph by slowing the rotor to 80% of its hovering design rotational speed. At this rotational speed the aircraft rotor will be operating at an advance ratio greater than 1.0. This forward speed represents a 100% increase over the forward flight speed of the pure helicopter.

Having examined the speed improvements for winged and compound helicopters, mention must be made of the additional benefits, the penalties and the expected engineering problems associated with these types of solutions.

A primary compromise might be the hovering performance. During hover the air flow through the rotor impinging on the wing creates a download. The download increases the required hovering power for a given gross weight and is given by the following simplified relation (from Reference 4):

$$\frac{\text{Induced power with download}}{\text{Induced power-no download}} = \frac{1}{(1-f_v/A)^{3/2}}$$

where

f_v = vertical drag area of the wing

A = disc area of the rotor

The download effect is plotted in Figure 5. An installed power loss of 10% is quite common for the addition of a small wing under a given rotor. However, the wing improves the hovering performance indirectly. Since unloading the rotor extends the blade stall threshold, this allows a reduced rotor solidity and/or an increased tip speed for an increased hovering efficiency. A 30% unloading of a typical rotor increases the stall threshold about 46 mph. If a higher speed is required and full advantage is taken of the wings, a hovering power savings of about 20% can be realized by optimizing the rotor more for hovering' i.e., the compromise between hovering performance and cruise speed is less for an unloaded rotor than a loaded rotor. For a given high speed cruise requirement, these two effects tend to cancel.

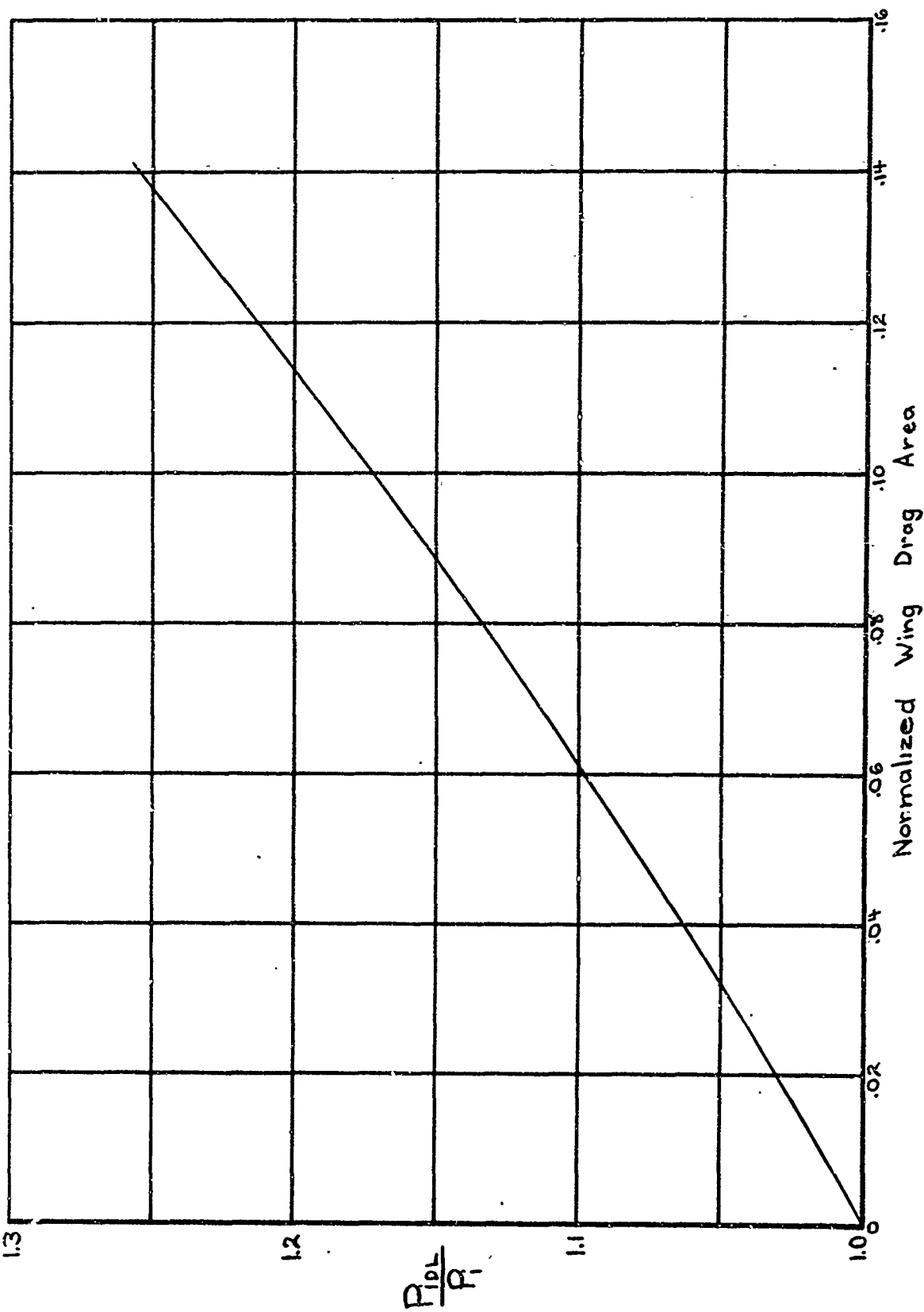


Figure 5: Induced Power Download Effects vs. Normalized Drag Area

Besides extending the flight speed, the addition of a wing has other aerodynamic advantages. Generally, it is more efficient to have a wing to carry part of the lift at speeds above 138 knots. Of course, these speeds usually require the addition of auxiliary propulsion also. Typical shaft power savings are approximately 100 hp. at 161 mph for a 7800 lb. helicopter requiring 1000 shaft hp., and 200 hp. at 201 mph for a 9200 lb. helicopter requiring 1050 shaft hp. and 1535 lbs. of auxiliary jet thrust. Figure 11 in Reference 3 indicates that the compound helicopter can develop a lift-to-drag ratio equivalent to the maximum lift-to-drag ratio of a pure helicopter at a speed increase of 46 mph. Also, the compound helicopter maintains a low but not prohibitive lift-to-drag ratio at much higher speeds.

The slowed rotor compound exhibits higher aerodynamic efficiencies than the compound rotor. Reference 2 indicates that the slowed rotor compound may obtain lift-to-drag ratios around 24 at $u = 1.6$ compared to a fully loaded rotor's lift-to-drag ratio equal to 12 at $u = 0.5$. Because of its lower rotational speeds; the unloaded slowed rotor will be more aerodynamically efficient than the purely unloaded rotor. For the slowed rotor to maintain these exceptionally high lift-to-drag ratios, a 70 to 80% blade unloading must be maintained at a proper cruise altitude. A typical disc loading would be 3 psf at an altitude greater than 20,000 feet.

A general improvement in the oscillatory loads experienced by the rotor results from compounding. These lower vibrational loads are readily appreciated by the pilot.

Some stability and control problems are alleviated by compounding. A noticeable improvement in maneuver characteristics results particularly for a cantilevered rotor. There are no transition problems from rotor-loaded to wing-loaded forward flight. The unloaded, articulated rotor requires both rotor control and conventional flight controls at higher speeds, but the cantilevered rotor may fly at higher speeds using only the rotor for control.

At higher forward speeds the rotor will be operating at high advance ratios--particularly for the case of the slowed rotor compound. When the advance ratio approaches one, the normal control response of the vehicle degenerates and lateral control becomes increasingly difficult for the pilot. A cyclic pitch input becomes "collective" in its effect on the vehicle's motion and a collective pitch input becomes "cyclic." For instance, when $u = 1$, the entire retreating blade at the 270° azimuth position (See Figure 2) is in reverse flow, and the net airflow is from the trailing edge to the leading edge. Consequently, a blade position normally described as a positive blade angle of attack is actually a negative blade angle of attack with respect to the reverse flow creating a download on the retreating blade. Increasing the collective pitch increases all the blade angles of attack increasing the lift on the advancing blade and increasing the download on the retreating blade. A cyclic pitch increment increases the angle of attack of the advancing blade increasing its lift and reduces the angle of attack of the retreating blade reducing its download.

When operating at advance ratios near one, cyclic pitch increments increase the rotor thrust and collective pitch increments produce a rolling moment. Some type of advance-ratio-sensitive control augmentation will be necessary to counteract this control interchange and permit safe operation at high advance ratios.

Similar to normal helicopters, entry into autorotation with a compound is a potential problem. Autorotation difficulties arise from two problems--roll control and rotor speed decay. After a power failure occurs, the vehicle loses speed and the rate of sink builds up increasing the wing angle of attack. One wing invariably stalls first requiring a roll moment correction. Since the rotor is unloaded, correctional inputs are very difficult to apply. This is particularly true for an articulated rotor without a large hinge offset. Although the problem is less severe with a cantilevered rotor, it still exists. The XH-51A compound has mechanically applied spoilers on the wings which allow the pilot to immediately load up the rotor under emergency conditions by "killing" the wing's lift. The decrease in rotor speed before entering autorotation also presents a problem. Wing lift changes with small attitude changes make it difficult to balance autorotation forces. Proper control of the aircraft attitude allows the pilot to reduce the air speed and make a safe entry into autorotation. The procedure used on the Lockheed cantilevered rotor is to "pop" the spoilers as soon as an engine failure is detected and maneuver into a decelerating turn.

High speed dynamic problems are the primary engineering stumbling blocks in developing operational, high speed compounds. The lightly loaded rotors are sensitive to changes in rotor disc angle of attack caused by gusts and maneuvers. To prevent over-loading of the rotor, the compound helicopter will require a "bob weight" or some other g sensitive, automatic blade angle control device.

There are three other basic dynamic problems which occur at high forward flight speeds.

- 1) A reduction in damping which occurs with increasing advance ratios adversely affects the blade flapping stability. (For $u = 2.0$ articulated rotors are divergent in the flapping mode.)
- 2) The reverse flow condition over the retreating blades is the ideal classroom flutter model. The center of pressure is at the quarter chord, but the center of gravity and the elastic axis are at the three-quarter chord.
- 3) Blade flapping amplitudes become progressively worse as u increases. The solution to these problems may incur a considerable weight penalty or may require a departure from conventional blade design. The cantilevered rotor (particularly the "soft-in-plane" variety) appears to have excellent characteristics in the face of these problems (References 1 and 5).

These dynamic problems are worse for the "slowed rotor" since the advance ratios are higher at a given flight speed. The minimum percentage of the rotor design speed to which the rotor may be slowed is determined by:

- 1) The operation of the unloaded blade at reduced flapping and inplane frequencies
- 2) Rotor system gust sensitivities
- 3) Reverse flow vibration environment

Very little work has been done on rotors at advance ratios greater than one, but Reference 2 indicates that the probable minimum rotational speed will be around 75-85% of the rotor design RPM.

Finally, the penalties in weight and complexity must be examined in determining the utility of the Class I design solutions. Naturally, the addition of wings and auxiliary engines have a considerable weight penalty, and many of the speed records set for prototype compounds have been achieved only by using huge amounts of installed power to overcome high drag forces. The curves are based on projections of component, propulsion and empty weights for the different vehicles. Chart II presents a performance summary of the designs examined in Reference 3. These balanced power designs were developed from projected weight and aerodynamic data, existing engine data and a 200 nautical mile range requirement. (The results are felt to be conservative because of the strict maneuvering requirements placed on the designs.)

In conclusion, the performance of the lifting rotor can be improved for many helicopter missions by Class I solutions. Compounding is more beneficial at higher gross weights and the slowed rotor shows the greatest speed potential. Since a gas driven rotor becomes more competitive at high gross weights, a strong case may be made for a slowed, gas-driven compound rotor. There are no transmission problems and a greater flexibility in diverting power to auxiliary propulsion is allowed. Any telescoping rotor blade having a high tip speed for hover and a low tip speed for cruise has excellent performance potential for a compound rotor vehicle. Although the engineering problems are by no means solved and substantial risk is still involved, they appear to be relatively simple when compared to the other classes of design solutions.

CHART II

500 LB PAYLOAD	WEIGHT (LBS)	HP REQUIRED	V _{MAX} (MPH)
Helicopter	2250	310	171
Winged	2360	320	174
Compound	3800	600	202

3000 LB PAYLOAD	WEIGHT (LBS)	HP REQUIRED	V _{MAX} (MPH)
Helicopter	11500	2400	218
Winged	11900	2500	230
Compound	15000	32000	276

6000 LB PAYLOAD	WEIGHT (LBS)	HP REQUIRED	V _{MAX} (MPH)
Helicopter	27100	6380	240
Winged	27300	6400	250
Compound	33500	8100	311

CLASS II DESIGN SOLUTIONS

Forced Lead-Lag Rotor

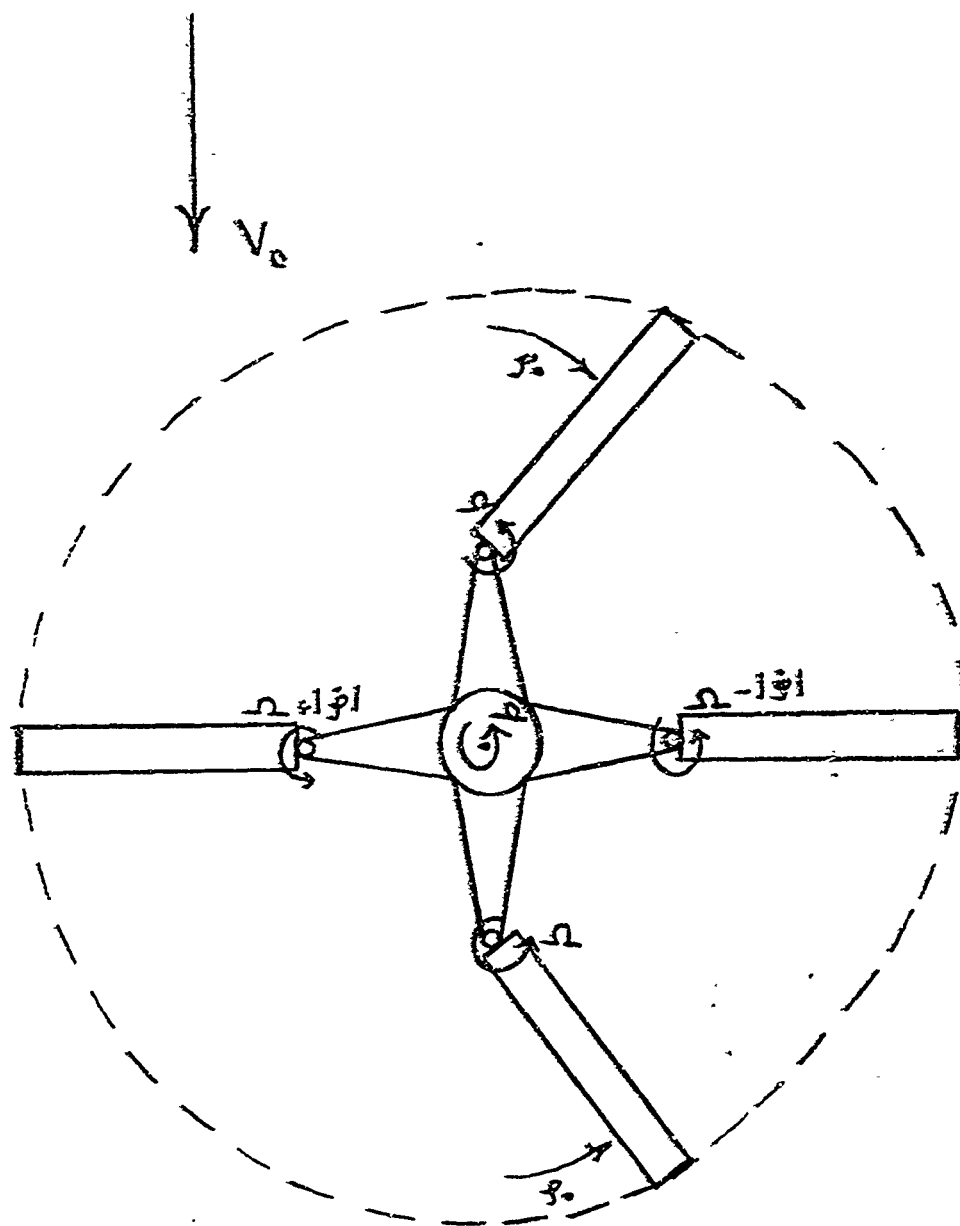
The Darschmidt forced lead-lag rotor is a novel approach to the problem of operating a rotor at high speeds in an unsymmetrical flow pattern. The primary advantage of this system is the equalization of the dynamic pressures on the advancing and retreating blades. The introduction of a properly phased, additional lead-lag motion decreases the net velocity on the advancing blades, and increases the net velocity on the retreating blades. (See Figure 7).

The aerodynamic advantages are obvious. A more symmetrical flow pattern produces a significant increase in lift/drag ratio, an increase in forward speed potential, and an improved thrust capability. In addition, smaller control angles are required for extreme flying conditions. Figure 8 illustrates the improvement in lift-to-drag ratio which may be achieved with a projected lead-lag rotor. This compares very favorably with the Class I design solutions, but at the expense of a smaller weight and power penalty. Figure 9 is a plot of the reverse flow boundaries for a lead-lag rotor with a hinge offset equal to $0.4R$. Comparing this with Figure 2, it is clear that much higher advance ratios are possible than with a pure rotor in forward flight. On a performance basis, the lead-lag rotor system is superior to other VTOL designs offering efficient high speed capabilities with very little weight penalty. (See Reference 8).

Unfortunately, the dynamic problems with this design solution are extremely complex. The forced lead-lag motion is only possible in the resonant condition which is a function of the hinge distance, the inertia of the blades and the amplitude of motion. A small hinge offset is desirable for aerodynamic efficiency, but a large hinge offset, or the addition of heavy bob weights is necessary to permit resonant motion. Consequently, the layout of the blade becomes very difficult. At high forward speeds, the amplitude of the lead-lag motion is very large. For the rotor in Figure 9, at an advance ratio equal to one, the lag amplitude required is around 90° . Large lead-lag amplitudes imply very asymmetric blade motions. Thus, the motion of the rotor blade center of gravity exerts a cyclical force on the rotor shaft and describes a lissajous pattern at a frequency equal to the blade number times the rotor rotational frequency. A large number of blades is desirable.

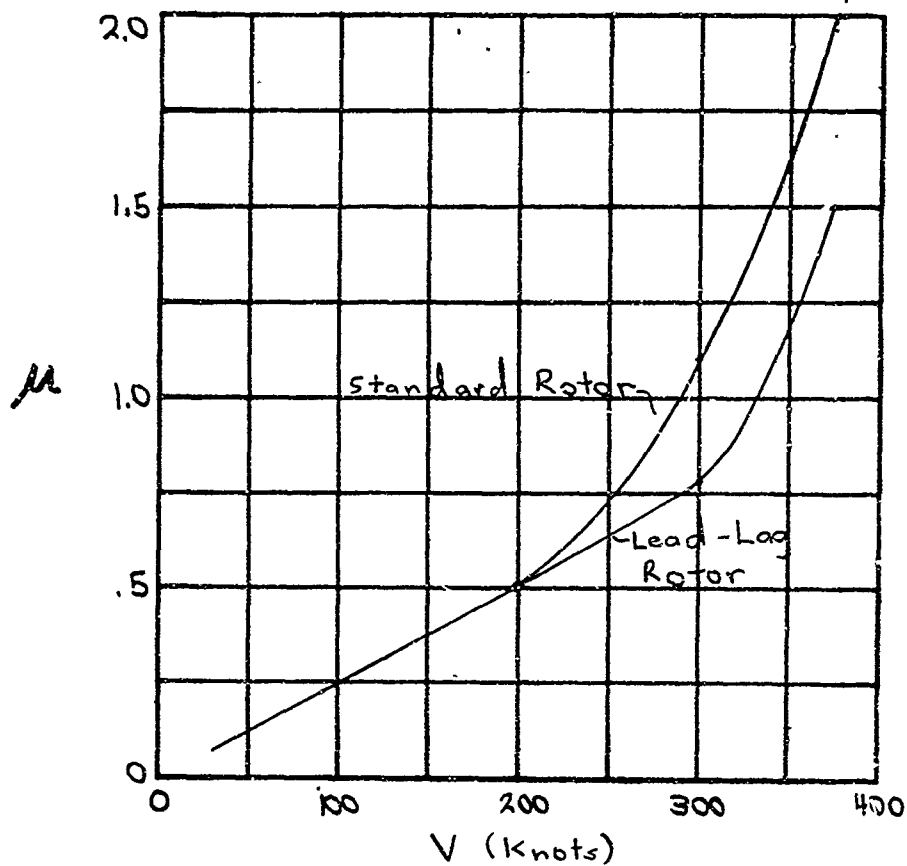
The loads on the exciting mechanism in the hinge joint are developed in Reference 7. Unfortunately, they are a function of the advance ratio, and tuning the system to eliminate the first harmonic for all advance ratios would require a variable hinge offset distance.

The potential performance benefits are excellent but the risks are very great. A test helicopter was built but scrapped after the tethering tests. The inventor/developer remains confident of the eventual utility of his design and attributes many of his problems to lack of experience in helicopter hardware. Undisputably, the concept is brilliant, but the mechanical complexities may prohibit operational development.

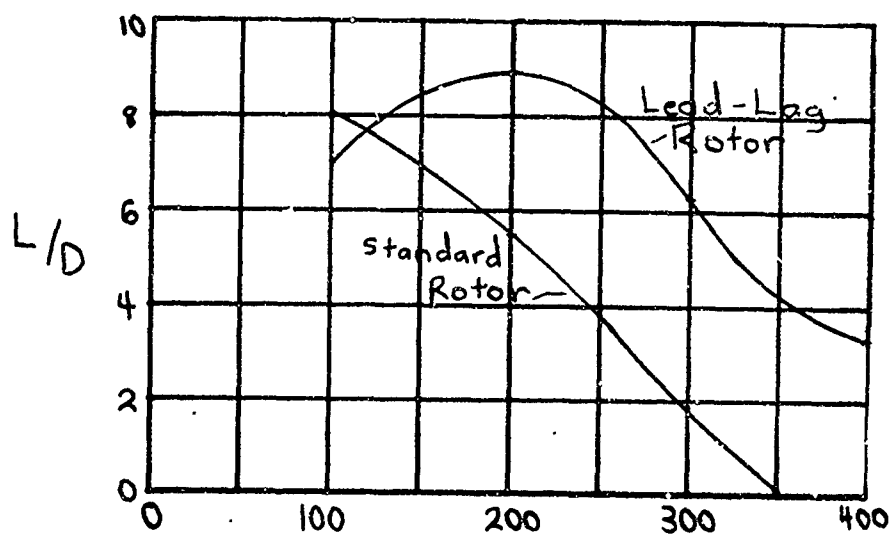


Typical Blade Pattern For A 4-Bladed Rotor

FIGURE 7.



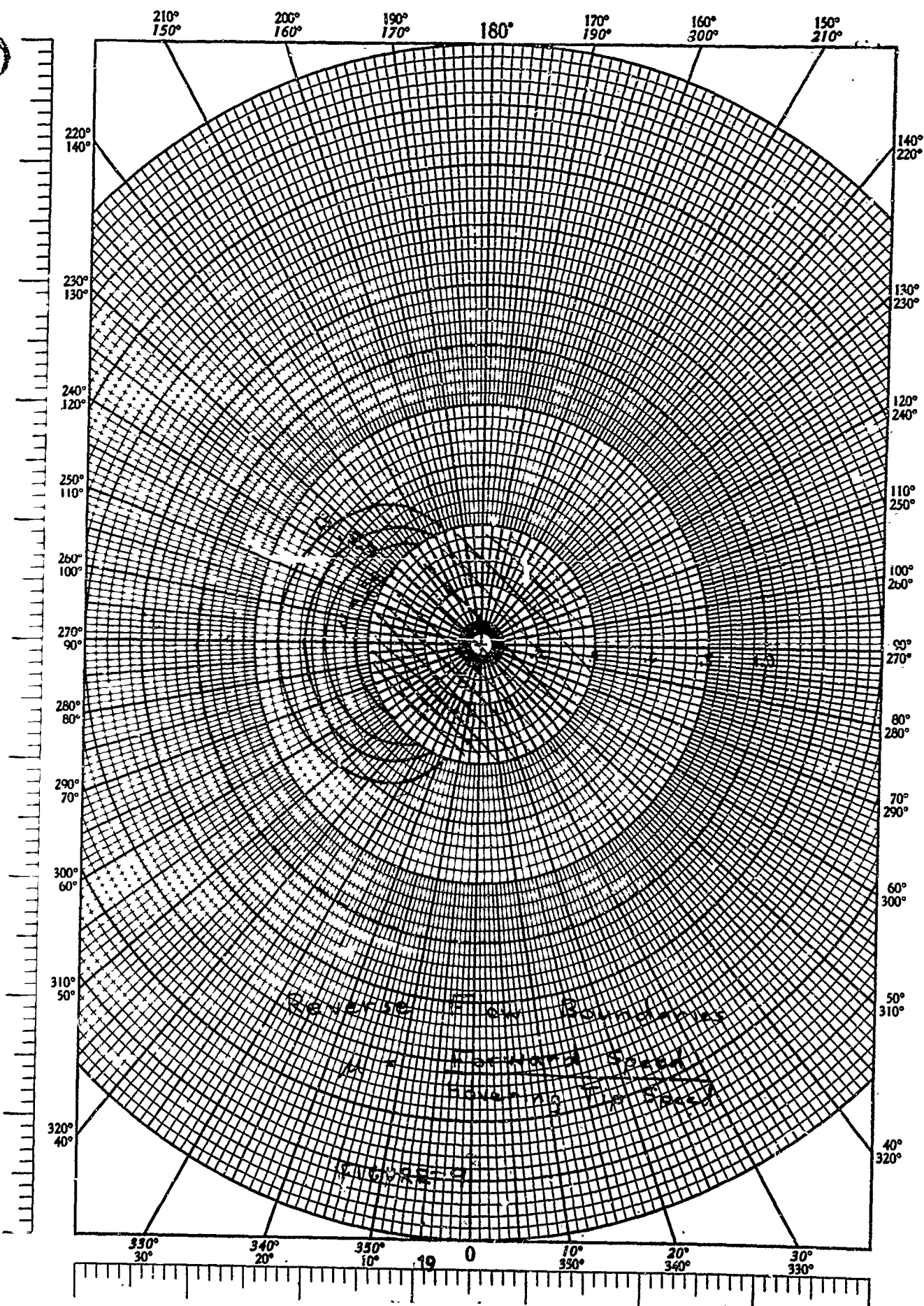
Ratio of Forward Speed to Tip Speed



Lift to Drag Ratio vs. Forward Speed (kts)

FIGURE 8

K.E. POLAR CO ORDINATE 359-31
HEUFFEL & ESSER CO



ADVANCING BLADE CONCEPT

Another fresh approach to the limited flight speed envelope of the lifting rotor is Sikorsky Aircraft's Advancing Blade Concept. Two counter-rotating rotors are mounted coaxially on a single shaft powered by the same transmission. The rotor uses two or three extremely stiff, cantilevered rotor blades. The coaxial system has the capability of providing a balanced lift independent of forward speed and does not require a tail rotor to compensate for the rotor torque.

To understand the benefits of the efficient ABC rotors, it is necessary to recall the specific nature of the problem. Because of the low aerodynamic velocities over the retreating blades, conventional rotors cannot produce a large, balanced lifting force. Laterally balanced lift is achieved by controlling the flapping motion through articulation or elastic deflection so that the effective incidence of the advancing blade is reduced and that of the retreating blade is increased. More of the lift is generated in the fore and aft sections of the rotor disc. Consequently, the rotor has a very poor lift-to-drag ratio when operating at high forward speeds.

The primary advantage of the Advancing Blade Concept is the use of a very stiff rotor which is rigid in flapping allowing a small airfoil incidence to be maintained over the entire rotor disc. Consequently, an efficient generation of lift at a high L/D ratio may be maintained. The overturning moment caused by the unbalanced rotor lift is equalized by the moment of the opposite unbalanced rotor. The generation of sufficient lift is no longer dependent on a low forward speed when the retreating blade is not stalled. If the counter-rotating rotors are in autorotation with a low tip speed during cruise, the forward speed of the vehicle is limited primarily by its drag. With the addition of a propeller or ducted fan powered by the gas turbines which are used to power the rotor in hover, very high forward speeds -- as high as 450 mph -- are possible. Assuming that the hub interference drag is not too high, these speeds may be achieved while still maintaining reasonable aerodynamic efficiencies.

There are three major problem areas for the ABC concept. These are the rotor hub moments, possible flapping excursions and noise.

Even the use of stiff blades may not prevent destabilizing, flapping motion on the retreating blades resulting in severe dynamic problems and high drags. Reference 9 investigates this problem by solving the equations of motion for a single rotor assuming that the rolling moment on the hub is no longer zero. This implies that the tip path plane of the rotor has a non-zero lateral tilt. The calculations indicate that for a properly selected lateral tip path tilt, the flapping motion of the blade reduces the angle of attack for retreating blade and increases it for the advancing blade. The changes in blade angle of attack for a non-zero rolling moment are shown in Figure 10 as a function of rotation angle for various tip path tilt angles. These angular changes are precisely those that are desirable for an efficient rotary wing. The results in Reference 9 also indicated that "heavy" blades

with high first mode flapping frequencies should be used.

The structural loads which the blades and rotor hub are required to carry present very difficult design problems for conventional rotor solidity. Because of the laterally unbalanced load on the rotor, the hubs will have to carry large wing-like bending moments. The rotor blades will have large cyclic bending moments also which must be carried by the blade material, yet the blades must have an acceptable fatigue life.

The ABC rotor is predestined to have noise problems. The slapping of the second rotor's blades on the shed tip vortex of the first may create very high noise levels. Increasing the separation distance between the rotors will decrease the noise levels but will increase the hub-mast drag.

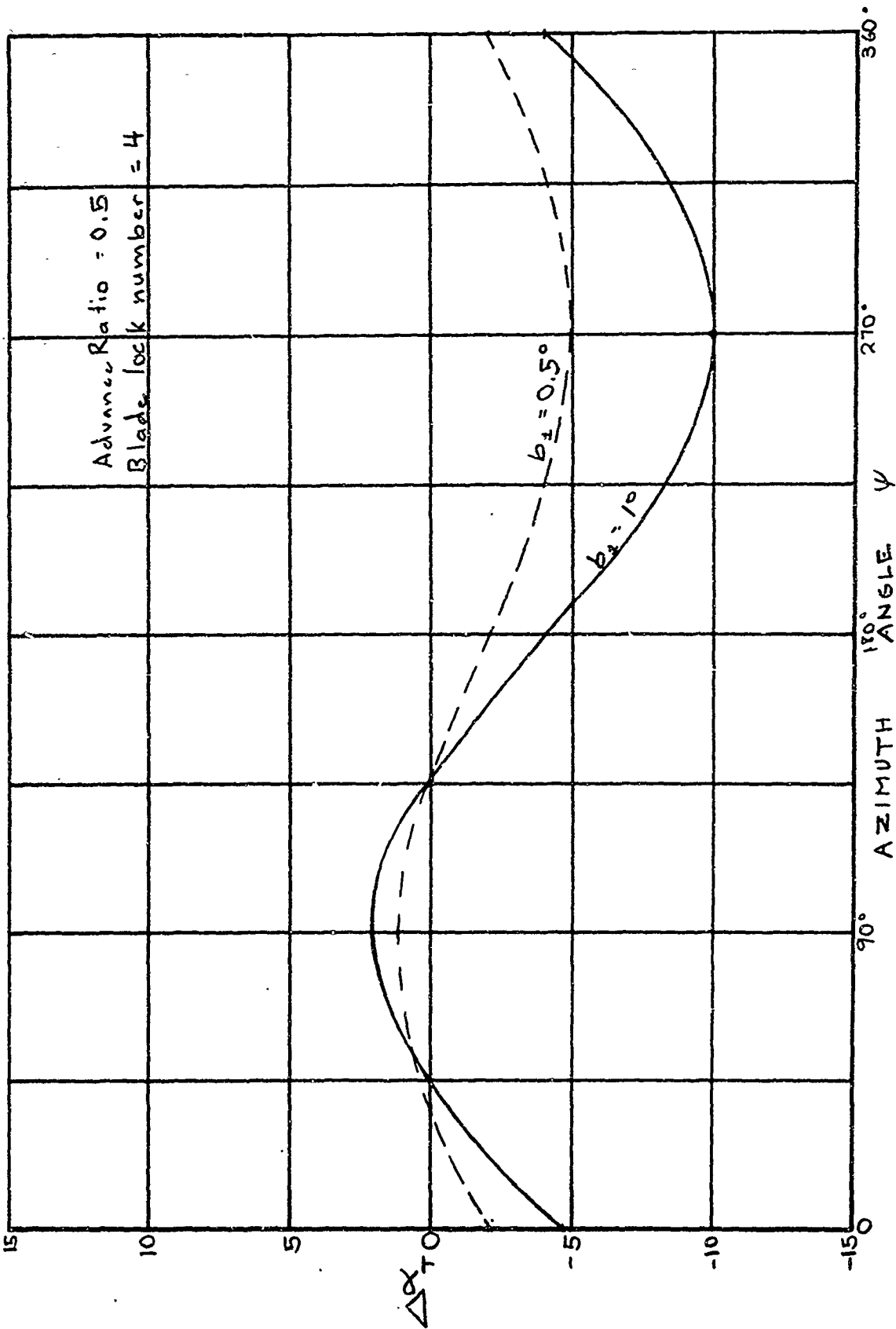
In summary, the Advancing Blade Concept is another promising solution to the extension of the lifting rotor's speed capability. Its' success will depend on the ability to fabricate light, stiff, fatigue-resistant blades and rotor hubs capable of meeting the severe structural loads encountered.

Jet Flap Rotor

The jet flap rotor is another concept which indicates a potential for increasing the forward speed envelope of the lifting rotor. The forward speed at which the retreating blade stalls may be increased by using a jet flap to control the air flow over the blade. At the same time, the jet flap corrects the lift imbalance occurring on rotors flying at ratios above 0.3. With a more sophisticated jet flap system employing a flap on both the forward and trailing edges of the rotor blades, it is possible to operate the rotor at a very high advance ratios--greater than one-- by generating lift on the portion of the retreating rotor blade in the reverse flow region. Using the jet flap on the leading edge of the retreating blade, a positive angle of attack in the reverse flow region may be achieved. Consequently, lift generated by the retreating blade in reverse flow may be used to balance the lift generated by the advancing blade.

With the single jet flap, an adequate flap deflection on the tip of the retreating blade allows a large lift coefficient to be maintained. Therefore, a lift comparable to that of the advancing blades crossing other azimuths is developed. The required deflection is approximately 30° for a jet-driven rotor and 60° for a shaft-driven rotor. The result of this is a significant increase in the lift-to-drag ratio for a rotor operating at a given tip speed. For very large rotors, the improvement in the L/D ratio of the rotor compares very favorably with the increased thrust required for the jet flap and the added complications. Also, since the stall of the retreating blades is delayed, the speed-range performance is improved.

Reference 10 evaluates conventional and jet flap rotors. The analytical investigation indicates that the jet flap rotor is capable of significantly higher forward speeds -- up to 340 mph -- but these velocities can only be



Change In Blade Angle of Attack With Tip Plane Tilt (b_1)



FIGURE 10

obtained by overpowering the stall of the retreating blades with large blowing forces. For the same unstalled flight conditions, a jet rotor requires more power than a conventional rotor of a similar design; but a jet-flap rotor is capable of generating a far greater thrust than a given conventional rotor of the same radius and solidity.

Use of a more sophisticated shaft-driven (or gas-driven) rotor with leading and trailing edge flaps conceptually allows rotor operations at extremely high advance ratios. Using a segmented rotor blade as described in Reference 11, the lifting moment of the advancing blades may be balanced by the lift obtained on the retreating blades using a jet flap control to develop high lift coefficients. With independent jet flap cycling for the different segments of the rotor blades, large total forces may be generated in spite of a large region of reverse flow. The power requirement for this system is also very high.

Since the power requirements for the jet flap system are very high, it is not too likely that this design solution will be developed for the cruise configuration. However, other characteristics of the jet flap rotor indicate that it might find a use as an addition to a Class III solution. Since the leading and trailing edge jet flap rotor has such excellent operating characteristics at high advance ratios, it might be used in conjunction with a stowed rotor. At transition speeds the aircraft would have surplus power available to operate the intricate flap system. Also, the large lifting force generated per rotor blade radius and solidity is desirable from a storage standpoint. This concept is most promising when considered in conjunction with a Class III design solution.

Controllable Twist Rotor

Another concept which is under investigation by Kaman Aircraft is the "controllable twist" rotor. Using a trailing-edge serve flap control and a conventional pitch horn on a torsionally elastic blade, it is possible to vary the blade twist angles as a function of forward speed. Independent control systems would be required for the servo flap and the pitch horn. Since twist requirements during hover and low speeds differ from those for high speeds, normal rotor blades are not optimized for either flight regime. With the controllable twist rotor, little compromise is necessary.

It is claimed that forward flight speeds of 230 to 345 mph are possible using this rotor blade concept. Since details of this concept are proprietary, it is difficult to determine the validity of the claim. Although it is theoretically possible to operate the rotor in a high advance ratio condition by twisting the blade so that positive blade angles of attack are maintained both in and out of reverse flow regions, it may not be feasible because of the structural forces produced and blade flapping excursions. Also, the controllable twist rotor does not compensate for the low dynamic pressures on the retreating blades as the jet flap rotor does by maintaining very high lift coefficients.

If the concept is feasible, a substantial performance gain is achieved while avoiding the weight penalties of additional lifting surfaces and propulsion devices.

Offset-Shaft Rotor

Payne's offset-shaft rotor, originally proposed in 1955, eliminates the retreating blade stall problem by reducing the lift required from the retreating blades. Laterally offsetting the rotor shaft from the vehicle's center of gravity or centerline produces a rolling moment allowing an unbalanced rotor lift distribution. This is functionally similar to the Advancing Blade Concept.

The offset-shaft rotor requires "stiff" hinges between the rotor blades and hub. The flexible cantilevered blade, an offset-hinge blade or a centrally located hinge with a restraining spring are all "stiff-hinged" rotor blades. An elastic stiffness in the centrally located flapping hinge or the centrifugal force stiffness of the offset hinge restrains the flapping motion of the rotor blades, and transmits pitching and rolling moments from the fuselage to the rotor. Laterally offsetting the rotor shaft towards the advancing blade side produces a rolling moment by the fuselage on the rotor shaft which must be balanced or eliminated. In the case of freely flapping hinges, the vehicle fuselage (and rotor shaft) would roll until the center of gravity is again centrally positioned under the rotor disc and nothing is gained. The stiff-hinged rotor transmits the rolling moment to the rotor disc requiring the rotor blades to generate a compensating moment to prevent the vehicle from overturning. The effect of this moment on the rotor disc is to require more lift from the advancing blades and less from the retreating blades implying a cyclic pitch adjustment reducing the retreating blades' angles of attack and increasing the advancing blades' angles of attack. Ideally, a particular offset distance will require nearly all of the rotor's lift to be produced by the advancing blades, and consequently the retreating blade stall problem is eliminated. A retreating blade will have negligible drag since its blade angles of attack are greatly reduced and the relative airflow velocities are small at high forward speeds.

Having eliminated the retreating blade stall problem, the forward speed limit is set by the advancing blades' mach number limitation (within the vehicle's power/drag constraints). Using an autorotating rotor and auxiliary cruise engines, forward speeds in excess of 400 mph may be possible. Speeds up to 350 mph are possible while still operating at advance ratios less than one.

Offsetting the rotor axis to increase forward speed is not free of any performance penalty. The basic offset rotor is less efficient when hovering since a reduction of the retreating blades' lift is necessary to counteract the rolling moment produced by the offset shaft. A larger rotor shaft offset yields a larger forward speed capability and suffers a larger hovering performance penalty. A variable rotor shaft offset eliminates the hovering efficiency degradation, but at the expense of increased mechanical complexity and an additional weight penalty. Lateral translation of the rotor shaft allows the rotor

shaft to be centrally located during hover and offset during forward flight. Another mechanism eliminating the rolling moment during hover is to use a single wing unloading only the retreating blades during forward flight. The rotor shaft could then be mounted conventionally, and the only hovering control problem and performance penalty would be the unsymmetrical download. The best choice is determined by the appropriate trade-off between additional weight and the hovering performance penalty. A projected design based on Payne's original vehicle proposal is illustrated in Figure 11.

The engineering problems presented by this concept are less severe than those of other design solutions. The justifications for the Advancing Blade Concept are also justifications for Payne's offset-shaft rotor. For advance ratios less than one, the offset-shaft rotor does not present any new rotor dynamics problems.

Payne's assymetric solution is unique since it uses the basic assymetry of the flow over the rotor. It is a very promising concept offering a significant forward speed improvement with a minimum of developmental risk.

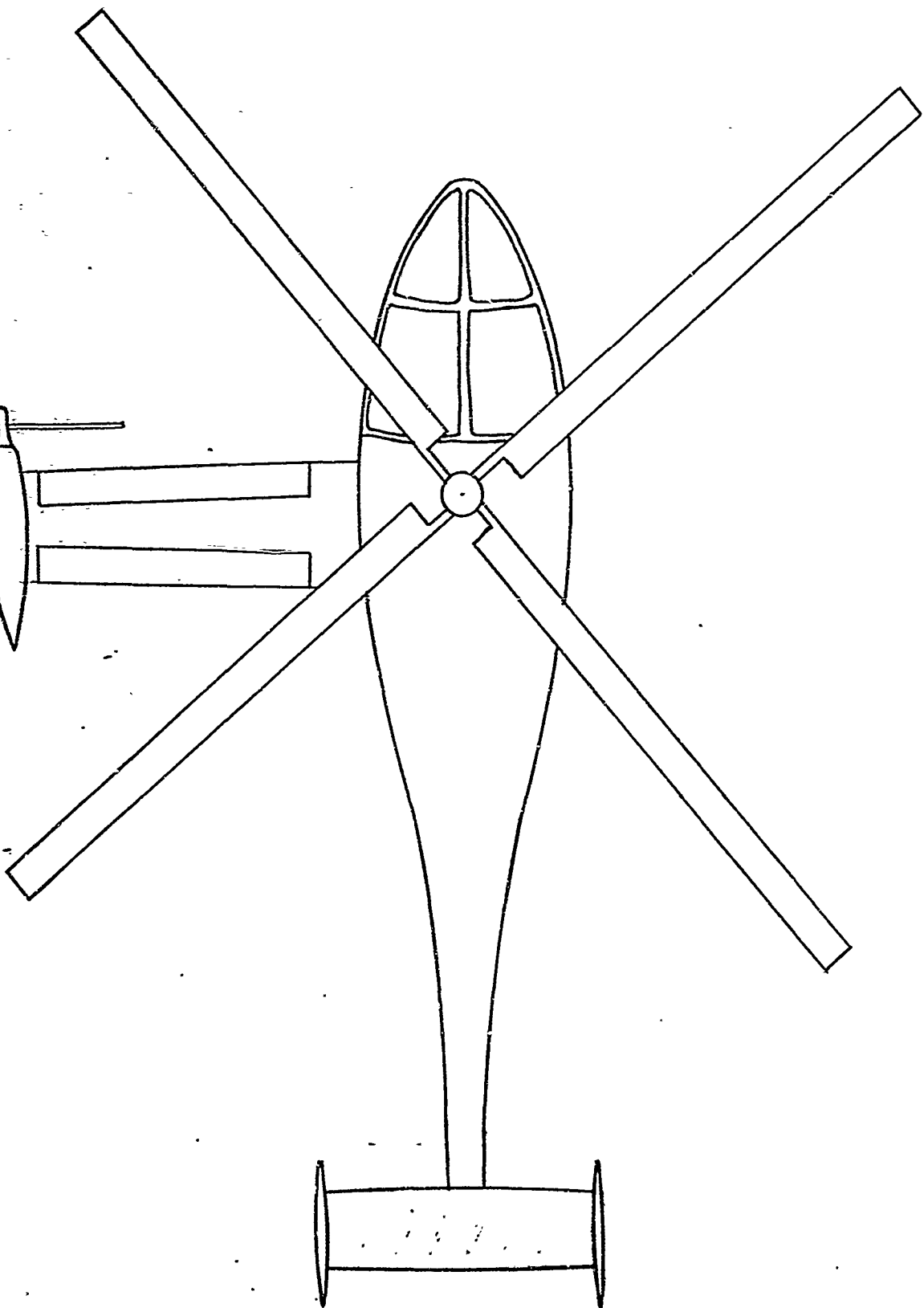


FIGURE 11

CLASS III DESIGN SOLUTIONS

Class III has the largest and most varied set of design solutions. The concepts discussed here are representative of most of the design approaches presently under consideration. Many of the propulsion systems are not well defined and performance estimations will be less accurate. The increased mechanical complexities are harder to evaluate in terms of a weight penalty. Many of these solutions are commonly called composite aircraft.

Rotor/Wing

The Lockheed Rotor/Wing concept uses a lifting rotor in the vertical flight mode which is converted into a fixed wing for the cruise mode. Four rotor blades with a high solidity compose a low disc loading rotor which provides lift for the aircraft. In the cruise configuration the rotor is stopped, and the blades are closed together to form a swept wing. The entire assembly is translated forward and faired into the fuselage behind the cockpit. (See Figure 12). In this manner, the rotor/wing concept uses a single structure to function as a rotor during vertical flight and as a fixed wing during forward flight.

Transition starts in the vertical flight mode with the gas generators providing full power to drive the cold cycle rotor. Low forward speeds are achieved by tilting the rotor/wing tip path plane forward. As the forward speed increases, part of the gas generator's propulsive power is diverted to cruise fans which provide forward thrust. When a sufficient speed is reached, the rotor/wing commences autorotation using only enough power for its rotor blade control. The rotor blade rpm is allowed to decay and the rotor is braked. The blades are swept together to form two wings and the entire assembly is moved forward and faired into the fuselage.

There are three major problems associated with the transition of the rotor/wing from the vertical flight to cruising mode. These three problems which are common to most stopped rotor vehicles are:

- 1) Roll trim at high advance ratios.
- 2) Rotor blade divergence at low and zero rotational speed.
- 3) Lift and pitch oscillation at very low rotor speeds.

The rotor/wing has the same lift imbalance problem during transition that a pure helicopter has at higher speeds. Decaying rotational speeds during transition increase the advance ratio creating the lift imbalance. Since there is no auxiliary wing to unload the rotor lift, a balanced rotor lift must be maintained even though the retreating blades may be entirely in a reverse flow region. A possible solution to this lift imbalance problem is a segmented rotor blade with leading and trailing edge jet flaps. Since less power is required at moderate forward speeds than during hover, the additional power may be used to increase the retreating blade lift coefficients to compensate for their low dynamic pressures. For the retreating blade in reverse flow

Rotor / Wing

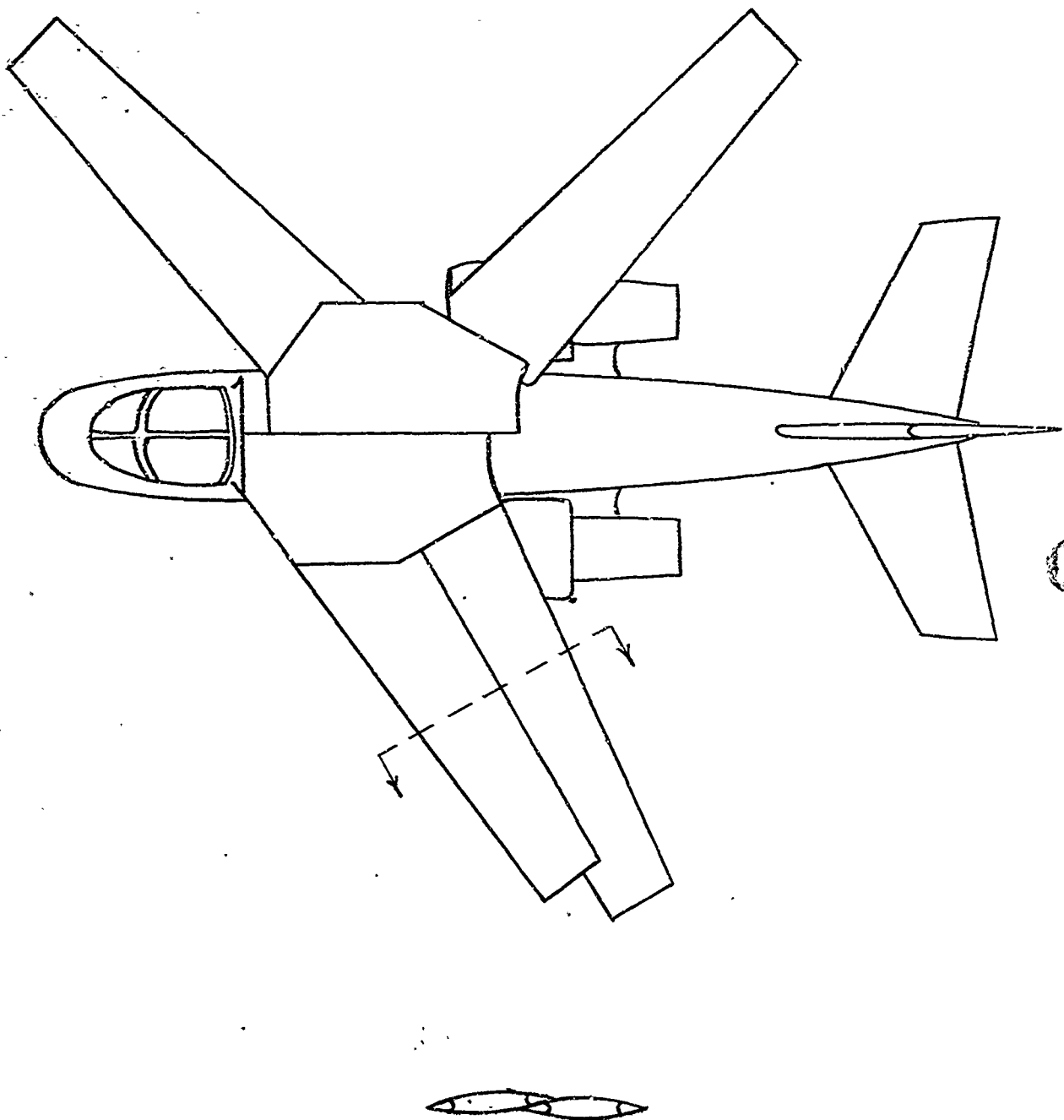


FIGURE 12

regions, the leading edge jet flap may be used to induce a positive angle of attack. The proper programming of the cyclic and collective control inputs for the different flap segments allow sufficient lift and a zero rolling moment to be maintained at all advance ratios. Reference 11 discusses this control system and calculates a sample lift and moment balance for $u = 1.4$.

Divergence of the wing/rotor blades at low or zero rotational speed is not a critical problem as it is for the normal stopped rotor. With the flap-wise stiffness inherent in the rotor/wing design, the blade will be able to withstand the bending moment generated at the moderate transition speeds.

Cyclical lift and the movement of the aerodynamic center around the hub may be a significant problem for the wing/rotor as there is no auxiliary wing to support the aircraft during transition. Reference 12 investigated this problem for rotors with three and four blades. The conclusions (which are discussed more thoroughly under the Lifting Hub Concept) indicate that movement of the aerodynamic center around the hub is minimal for a four-bladed rotor/wing because of the geometry.

After the rotor/wing blades have been folded together, the retraction mechanism shifts the entire assembly forward to maintain the proper relationship between the aerodynamic center and the center of gravity.

The rotor/wing concept combines the hovering performance of a moderate blade loading rotor and an efficient subsonic cruise performance for a penalty in reduction of disposable load. There is no inherent speed limit and the maximum forward speed is primarily a function of the installed power. The rotor/wing has equivalent or better performance than a high blade-loading, blown, conventional stowed rotor (Reference 11). This is generally the case if storage considerations restrict the conventional rotor size below the optimum design. These performance gains must be traded off against the reduction in disposable load. The mechanical complexity dictates a high cost, and the extensive control system must be highly reliable. A failure during transition would probably be fatal.

Hot Cycle Rotor/Wing

The Hughes Hot Cycle Rotor/Wing is commonly called the lifting hub concept. It differs from Lockheed's rotor/wing in that a rigid lifting rotor is stopped in flight to become a fixed wing without any geometrical transformation taking place. The Hughes rotor/wing may be simply described as a hot cycle rotor with a large triangular hub and short, wide rotor blades. During hovering, gas generators provide a high energy gas flow to the rotor tip jets to drive the rotor as a reaction turbine. During forward flight the gas generator output drives cruise fans which provide forward thrust (See Figure 13).

Hot Cycle Rotor/Wing

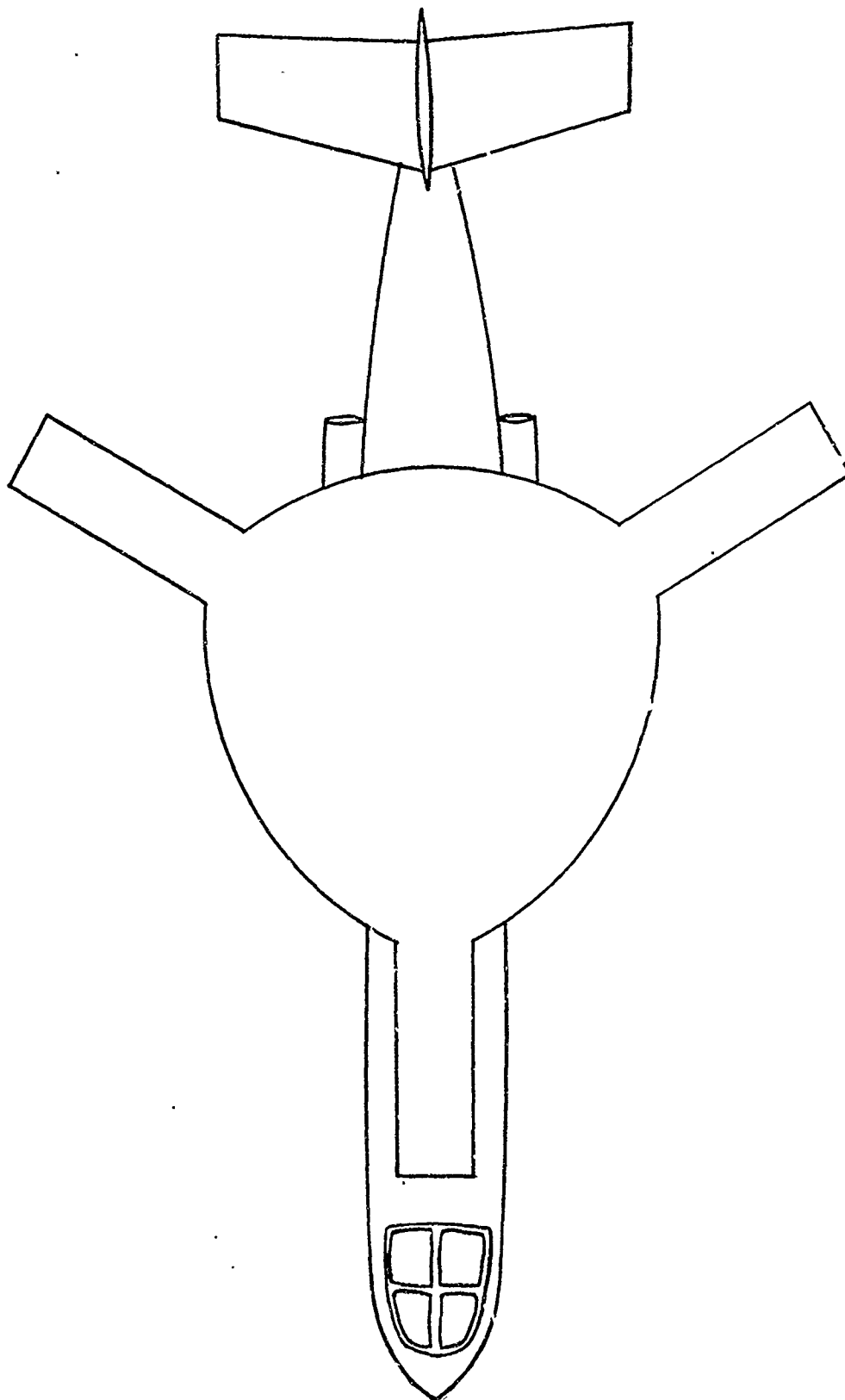


FIGURE 13

The transition from the hovering mode to the forward flight mode is relatively simple. The rotor/wing is powered by its tip jets up to a forward speed of 115 mph while using cyclic control on the rotors. Diverting part of the gas generator output into the cruise engines, the forward speed is increased. Autorotation is started by reducing the collective pitch and full power is diverted to the cruise engines. At a speed of 173 mph, the rotor/wing is slowed by raising the collective pitch, braked and locked against the fuselage. The forward blade is faired into the fuselage. The two remaining blades and the large hub act as a 30° swept wing in forward flight.

The lifting hub has essentially the same problem during transition as the Lockheed rotor/wing -- roll trim at high advance ratios, rotor blade divergence, and lift and pitch oscillation at low to zero rotational speeds. Rotor blade divergence at zero rotational speed is not a problem because of the stiffness of the stubby blades, their short length and the rigid attachments to the rotor/hub.

Roll trim at high advance ratios does not present as difficult a problem as for the Lockheed rotor/wing. At moderate forward speeds lift is generated on the central hub but it does not serve to unload the outer rotor as a wing does on a compound helicopter. Roll trim at high advance ratios may be provided by proper applications of cyclic and collective pitch. Reference 3 indicates that the control moments required during transition had been determined. It is asserted that they are within the capabilities of a pilot to handle although an automatic control system monitoring advance ratio is advisable.

The principal transition problem is the large attitude disturbance which will normally occur during the first or last revolution of the rotor. The attitude disturbance results from the rotation of the lift center of pressure in an elliptical path at a frequency that is simply the number of blades times the rotational speed. This may be corrected by large amplitude cyclic pitch automatically applied in phase. Also, the horizontal tail is capable of correcting these moments in some cases. The adoption of a four-bladed lifting hub will alleviate the disturbing moments without requiring automatic pitch corrections (Reference 12). Unfortunately, a four-bladed lifting hub cannot be converted into as acceptable a fixed wing.

The hover and cruise performance are compromised more than other Class III design solutions. The lifting hub requires about 30-35% additional power when compared to a conventional rotor in hover, and the cruise performance compares favorably only with a delta-wing. The primary advantage of the lifting hub is its simplicity, the absence of any major engineering problems and relative safety of the concept. Autorotation under a complete power failure is possible during any phase of the transition. Entry into autorotation under emergency conditions may be possible from the cruise configuration using the horizontal tail to counteract roll moments when engaging the rotor. The relative simplicity of the hot cycle rotor and propulsion system will probably imply a relatively low cost.

Tilt Prop-Rotor

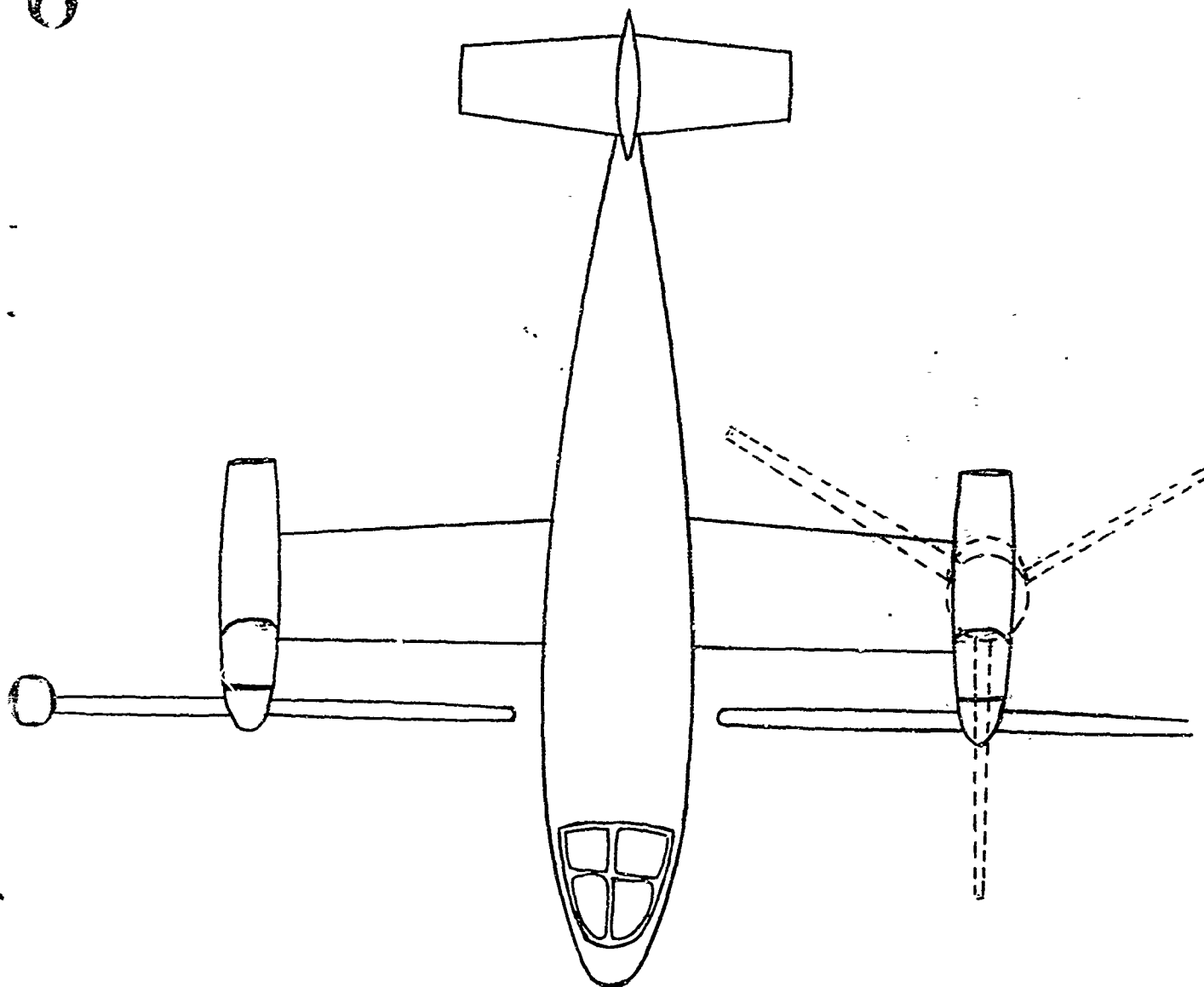
Tilting the low disc loading rotor 90° forward so the tip path plane is perpendicular to the forward flight path eliminates the rotor mach number limitation and reverse flow region. A solution of this type may be described as a typical aircraft with two combination propeller and rotors mounted on the wing tips (See Figure 14). During the hovering mode, the low disc loading rotors are tilted vertically to provide lift. During cruise the rotors are returned to the horizontal position providing propulsive thrust with the wing generating lift.

Typical prop-rotor design characteristics are a hovering tip speed of 750 ft/sec., and a variable cruise tip speed of 400-600 ft/sec. The speed variation is accomplished by using a variable RPM gas turbine optimized for off-design operation. The disc loading on the tip rotors is comparable to higher disc loading helicopters. A single propulsion system is used, and the wings have leading and trailing edge flaps to decrease the wing downloads during hover.

Transition is particularly simple for this design concept. Conversion from the vertical mode to forward flight may be made progressively as speed is increased or the speed may be increased above the wing stalling speed, and then the rotors are tilted forward 90° to the cruise position. The normal conversion time is approximately six seconds.

More development effort has been spent on the tilting rotor than on other Class III design solutions. Power and control transmission to the tilting rotors at the wing tips is difficult and requires considerable mechanical complexity. The major engineering problem yet to be solved is a whirl mode instability which becomes progressively worse as speed increases. For small deflections of the prop-rotor axis in pitch, a vertical aerodynamic force (among others) is produced which is proportional to the pitch angle. This is the primary energy transfer mechanism which--given the proper stiffness and damping characteristics--leads to the whirl mode instability of the rotor-pylon mounting. Although the whirl mode instability occurs at lower forward speeds for articulated, low disc loading rotors than for propellers because of the flapping and cyclic variations in pitch; the articulation also provides a means for the solution of the whirl mode instability problem. Using blades with sufficient torsional stiffness and a control gyro which is responsive to the rotor disc's axis movement, the induced pitch angle changes may be compensated for using the proper linkage from the control gyro to the blade pitch horns. With the cyclic driving force eliminated, there is no whirl mode instability, and the rotor may be limited only by the conventional forward speed limitation of a propeller aircraft.

With a simple transition procedure, an efficient hovering figure of merit, and a fairly high lift-to-drag ratio, the prop-rotor is an attractive solution. The prop-rotor does not have the high speed capability of other



Tilt Prop - Rotor

FIGURE 14

Class III design solutions, but in its speed range it is very promising. The prop-rotor should be a strong competitor against Class I and Class II design solutions for many military and commercial missions.

Trailing Rotor

The trailing rotor concept is an example of several design solutions which stop the rotor during forward flight but do not stow it internally. The trailing rotor evolved from the tilt prop-rotor concept and its purpose was to extend the forward speed to be competitive with other composite aircraft.

Two wing tip rotors are used to provide lift for vertical flight. During transition, the rotors are tilted to the rear, and trailed in a low drag configuration during forward flight. Gas generators provide power to operate the rotors for lift or to the fan for propulsive thrust.

As with many other Class III design solutions, a segmented transition is necessary. In the vertical flight mode, the gas generators provide all their power to the tip rotors. As the forward speed is increased, gas generator power is diverted to the cruise engines and the wings provide lift. The rotors are tilted to the rear in autorotation. Forward speed is increased while the rotor pylons are tilted back to the horizontal. The rotor rpm is reduced and the blades are folded downstream.

The rotors do not require any power during transition, and emergency landings may be made. The forward speed is limited by the drag of the vehicle, and dynamics during folding are not expected to present unsolvable problems. There is little difference between the trailing rotor concept and the stowed rotor. Although the dynamic problems are less severe, the cruise performance will be inferior because the folded rotor blades are trailed in the airstream.

Stowed Rotor Concept

The stowed rotor concept is basically a high wing loading aircraft with a lifting rotor and anti-torque tail rotor added to give an efficient vertical flight capability. Gas generators provide thrust to power a gas-driven or shaft-driven rotor during the hovering mode and cruise fans or propellers for forward flight. During transition, the rotor is stopped, folded and retracted into the fuselage providing an exceptionally clean configuration for forward flight.

The transition from the hovering mode to the cruise configuration is more difficult for the stowed rotor. During vertical flight the gas generator delivers full power to the rotor. Tilting the vehicle provides a forward thrust component and the forward speed is increased. As the forward speed increases, the wings unload the rotor, and power is diverted to the cruise engine. The aircraft reaches the wing's stall speed and the rotor autorotates.

After the rotational speed decays sufficiently, the rotor is braked, the rotor blades folded; and the entire assembly is retracted or faired into the fuselage.

The stowed rotor has to overcome the same transition problems discussed earlier -- the roll trim problem, rotor blade divergence, and the lift and pitch oscillation. The roll trim problem is fairly simple for the stowed rotor concept. The fixed wings provides balanced lift at high rotor advance ratios. By maintaining an identically zero rotor thrust during the stopping and starting cycle, pitching and rolling moments will not be generated.

Although the lift and pitch oscillation problem for low rotor rpm degenerates when the net rotor thrust is held to zero during the starting and stopping cycle, gusts could create a net force and consequently a rolling moment. Some form of automatic feathering control which compensates for external angle of attack disturbances will be necessary to limit rotor blade oscillations during stopping and starting.

The main transition problem because of the slender, stowed rotor blades is the possible rotor blade divergence at low or zero rotational speeds. Reference 2 indicates that a minimum divergence speed for a typical stowed rotor is 167 mph at an azimuth angle = 225° . This value was determined experimentally by wind tunnel tests. These results imply that the rotor must be folded before a forward speed of 167 mph is reached.

The center of gravity shift during transition adds another mechanical complexity. In most stowed rotor configurations, the retraction mechanism usually includes a forward shift of the entire assembly -- rotors, hub and controls, when the rotor is stowed. This is in addition to the vertical movement required.

There are no flutter problems since the flutter speeds for the trailing, stopped rotor blades are much higher than 167 mph.

The stowed rotor concept has the best potential high speed performance of any design solution, but the efficient cruise configuration is achieved only with a considerable expense in additional weight and mechanical complexity. The hovering performance is somewhat inferior to other designs because storage constraints imply higher than normal disc loadings, and a low hovering figure of merit results.

An attractive solution for this problem is the variable length rotor blade. Several possible designs have been (or are being) studied. These include the telescoping rotor where the blade simply expands in length similar to an automobile antenna, the flyball system which might be described as a centrifugal force operated, spring-loaded "jack knife" and the "wire-attached" system where a constant length rotor blade is free to trail out on two cables. The primary advantage of these variable diameter rotors is that they ease the storage constraints. Prior to stopping, the blade would be reduced to its short length so the divergence problem would be precluded. The shorter

blade length prior to folding would allow a higher transition speed which would mean a smaller wing. Some of these blade mechanisms would hardly be more complicated than a ducted, flapped rotor. An expandable rotor blade offers a large improvement in the hovering performance of a stowed rotor making the stowed rotor concept far more attractive.

Comparisons and Conclusions

Having examined the speed limitation problem inherent with low disc loading rotors and a group of proposed solutions to this problem, the next logical step would be to compare their performance capabilities, costs of performance and development risks to see which designs are most attractive. Such comparisons are discussed in the trade literature but the design problems proposed and the assumptions used usually favor a single design. Consequently, there is a great deal of confusion as to which design is "best". One possible opinion is that many of the designs are reasonably competitive with each other, and the "best" seems to depend upon the figure of merit or the explicit design assumptions. The assessment of projected development risks is very difficult, and it is not implausible to contend that this is the reason so many imperfect VTOL prototypes have been produced, and no operational vehicle other than the helicopter (and now the Harrier) are in operation. When a fundamental, yet-to-be-solved problem was confronted in a previously selected design solution, a decision was usually made, because of the abundance of many competitive design solutions, to develop an alternate solution which hopefully would not have any fundamental, unsolved problems. The result has been the proliferation of research vehicles.

As an alternative to selecting a "best" design, a chart of potential problems has been developed for the design solutions discussed previously. If the design solutions have reasonably competitive performances, which seems to be the case, then the design complexity and technical feasibility (which determine the cost and development risk) become increasingly important. Using Chart III it is possible to identify problem areas common to several design solutions. The allocation of resources to these areas would provide a substantial return in information and experience applicable to the largest number of design solutions. The investigation of problems rather than developing prototype, research vehicles may result in a minimum duplication of effort and the maximum utility. A more knowledgeable selection from the candidate systems could then be made with a greater assurance of the eventual success of the design vehicle.

Ten problems relating to rotor blade control and design have been identified. All rotor blades are subject to many of these problems. Consequently, a design solution is considered to have a problem in a given area when its operating characteristics and design layout imply a more serious problem than for an existing helicopter rotor. Most of these problem areas are self-explanatory after reading the descriptions of the design solutions,

Design Solutions										
Compound	X		X	X						
Slowed Rotor Compound	X	X	X	X						
Forced Lead-Lag Rotor					X	X	X			
Advancing Blade Concept	X	X	X							
Jet Flap Rotor	X		X				X	X		
Controllable Twist Rotor	X	X	X				X			
Offset-Shaft Rotor (u_{c1})		X								
Rotor-Wing	X		X				X	X	X	
Hot Cycle Rotor-Wing	X								X	X
Tilt Prop-Rotor							X		X	
Trailing Rotor		X					X			
Stowed Rotor		X	X	X						X

Potential Problems

Cyclic-Collective Pitch Interchange	
Blade Flapping Dynamics	
Reverse Flow Blade Flutter	
Gust Loading	
Large Lead-Lag Forces and Blade Fatigue	
Rotor Shaft Cyclical Forces	
Mechanization of Cyclic and Collective Pitch Control	
Cyclic Jet Flap Control	
Whirl Mode Flutter	
Rotor Control During Rotor Braking	
Center of Lift Oscillation at Near Zero Rotational Speeds	

Chart III

but a brief explanation of the designated problem areas follows to minimize any confusion:

Cyclic-Collective Pitch Interchange -- For the first order cyclic pitch variations, roll control of the vehicle degenerates because of a cyclic and collective pitch interchange which gradually develops near $u = 1.0$ and is complete at $u = \infty$.

Blade Flapping Dynamics -- This general problem refers to the greater than usual flapping excursions of the rotor blades, the attendant large bending moments and the possible rotor blade fatigue problem. Lower rotational speeds and higher forward speeds reduce the stability of the blade flapping motion and increase the bending moments carried throughout the blade. Similarly, decreasing the lift carried by the retreating blades and not the advancing blades adversely affects the blade flapping motion.

Reverse Flow Blade Flutter -- Rotor blades which operate in large reverse flow regions must satisfy an additional set of design constraints to preclude blade flutter.

Gust Loading -- Conventional rotor blades, unloaded or at low rotational speeds, may be very sensitive to gust loadings.

Large Lead-Lag Forces and Blade Fatigue -- This refers to more severe lead-lag forces relative to a conventional helicopter rotor.

Rotor Shaft Cyclical Forces -- The asymmetric motion of the forced lead-lag rotor leads to a non-zero centrifugal force exerted on the rotor shaft by the individual rotor blades.

Mechanization of Cyclic and Collective Pitch Control -- The mechanical transmission of cyclic and collective pitch inputs is more complicated than for a conventional rotor. For instance, the forced lead-lag rotor has control inputs transferred across two rotational axes, or the rotor-wing requires a complex swashplate (or other mechanism) to produce higher order cyclic pitch variations.

Jet Flap Rotor Control -- This refers to problem associated with blown flaps which may be used to control blade angle of attack variations and aerodynamic twist.

Whirl Mode Flutter -- This is the divergent oscillation of the rotor-pylon combination.

Roll Control During Rotor Braking -- Maintaining a smooth, no roll flight during transition is a problem for stopped rotor vehicles, and may require some form of gust-alleviation device with compensation for cyclic-collective pitch interchange.

Center of Lift Oscillation at Near Zero Rotational Speeds -- Similar to the last problem, three-bladed rotors may produce a large, peak rolling moment during their last revolution prior to stopping. This peak rolling moment is greatly reduced for four-bladed rotors.

The problems indicated for each design solution in Chart III were drawn from the solution descriptions presented previously. Although the "X's" do not indicate the relative magnitudes of the problems, useful conclusions may still be inferred.

From an examination of the matrix, there are four major problems -- Cyclic-Collective Pitch Interchange, Blade Flapping Dynamics, Reverse Flow Blade Flutter and the Mechanization of Cyclic and Collective Pitch Control. The last major problem maybe eliminated since its entries in the matrix indicate that it may be further divided into two distince sub-problems. One is the generation and phasing of unusual cyclic pitch inputs to achieve rotor lift in reverse flow regions, and the other problem is the mechanical linkage between a normal swashplate and the blades across an unusual transmission path.

The Blade Flapping Dynamics and the Reverse Flow Blade Flutter problems may be viewed as two parts of a single rotor blade design problem. Rotor systems that are slowed, stopped or operated at very high forward speeds all have these two problems. The blade flapping stability problem is made more difficult by decreasing centrifugal stiffness. Reverse flow blade divergence and the need for compatible solutions to the blade flutter problems in both normal and reverse flows must eventually cause a departure from conventional blade design practice. In general, weight limitations require that these problems be solved, in part, by increasing the blade flapping and torsional stiffness through the use of wing-or-propeller-like blade aspect ratios and constructions. The investigation and design of a high-stiffness rotor blade may be a partial solution to the problems of many design solutions.

Finally, many of the rotor systems will experience an interchange between cyclic and collective pitch functions becoming noticeable around $u = 1.0$ and complete at $u = \infty$. Safe operation at high speeds for many of the design solutions demands an augmented control system that allows for the effects of the control interchange as it develops.

Returning to Chart III and using the number of crosses as a selection criterion, the offset-shaft rotor (operating at $u < 1$) has the least number of problems, and thus may be the most feasible design solution. (At higher advance ratios, it would only be subject to the three other problems that are common to all the other design solutions operating at advance ratios greater than one and would not have their additional problems.) With a maximum forward speed near 350 mph, the offset-shaft rotor ($u < 1$) is very attractive as a general concept for investigation.

In conclusion, the allocation of resources to the design and testing of a high stiffness rotor blade capable of operating at low rotational speeds and advance ratios greater than one, and an investigation of the control interchange problem should be made. Because of the significant increase in forward speed and the small penalty in complexity, a conversion of an existing helicopter to an offset-shaft helicopter is also warranted to demonstrate the feasibility of the concept and ultimately demonstrate solutions to the Blade Flapping Dynamics Problem.

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